grc4f v1.0: a Four-fermion Event Generator for e^+e^- Collisions

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Abstract

grc4f is a Monte-Carlo package for generating $e^+e^- \to$ 4-fermion processes in the standard model. All of the 76 LEP-2 allowed fermionic final state processes evaluated at tree level are included in version 1.0. grc4f addresses event simulation requirements at e^+e^- colliders such as LEP and up-coming linear colliders. Most of the attractive aspects of grc4f come from its link to the GRACE system: a Feynman diagram automatic computation system. The GRACE system has been used to produce the computational code for all final states, giving a higher level of confidence in the calculation correctness. Based on the helicity amplitude calculation technique, all fermion masses can be kept finite and helicity information can be propagated down to the final state particles. The phase space integration of the matrix element gives the total and differential cross sections, then unweighted events are Generated. Initial state radiation (ISR) corrections are implemented in two ways, one is based on the electron structure function formalism and the second uses the parton shower algorithm called QEDPS. The latter can also be applied for final state radiation (FSR) though the interference with the ISR is not yet taken into account. Parton shower and hadronization of the final quarks are performed through an interface to JETSET. Coulomb correction between two intermediate W's, anomalous coupling as well as gluon contributions in the hadronic processes are also included.

PROGRAM SUMMARY

Title of program: `grc4f`
Program obtainable from: CPC Program Library, Queen's University of Belfast, N.Ireland (see application form in this issue) and from ftp.kek.jp in directory kek/minami/grc4f.
Computer for which the program is designed and others on which it is operable: HP9000 and most of the UNIX platforms with a FORTRAN77 compiler
Computer: HP9000; *Installation*: National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki, Japan
Operating system: UNIX *Programming language used*: FORTRAN77
High speed storage required: 36 Mbyte *Card image code*: ASCII
Key words: W-boson, Z-boson, e^+e^- colliders, four-fermion, ISR, FSR, QEDPS, Coulomb correction, event generator, parton shower, hadronization, color base.

Nature of physical problem
Study of W boson physics and of background processes for new particle search at LEP-2 and beyond.
Method of solution
The automatic amplitude generator `GRACE` is used to get the necessary helicity amplitudes for all the four-fermion processes. Specific corrections are then introduced to deal with the gauge boson width, the radiative corrections, the color assignment, the hadronization, the coulomb correction and the anomalous coupling.
Typical running time
The running time depends on the number of diagrams of the selected process, on the required cross-section accuracy and on the applied cuts. For instance, the process $e^-\bar{\nu}_e u\bar{d}$ takes 20 minutes to reach a 0.5% accuracy on the total cross section integration with HP-735/99.

1. Introduction

The main purpose of the LEP-2 experiments is to measure the properties of the W-boson with a high level of precision by its direct pair production. At the Z^0 peak (LEP-1 energy), two-fermion final states produced by the Z^0 decay are, by far, the most important processes. At higher energy, charged W-boson being necessarily created in pair at e^+e^- colliders, the cross-section is dominated by four-fermion processes. However, other production mechanisms may also lead to four-fermion final states like Z^0 pair or two-photon like production. In addition, some four-fermion processes contribute heavily to the background for new particle searches due to their large missing energy. In this paper, a four-fermion event generator, `grc4f`, is presented. It provides a convenient way of computing cross-sections under the complex cuts, acceptance and resolution of the collider experiments.

It is based on the `GRACE`[1] system which generates automatically the matrix element in terms of helicity amplitudes (supplied by the `CHANEL`[2] library) for any process once the initial and the final states have been specified. At present, the system has been completed only at tree level in the framework of the standard model for electroweak and strong interactions. Fermion masses are non-zero and helicity information can be traced down to the final state particles. In addition, a kinematics library has been developed to cover the requirements of each process topology (weeding out multidimensional singularities) to get a faster convergence of the Monte-Carlo integration over the phase space. The `grc4f` package is actually a collection of 76 $e^+e^- \to$ 4-fermion processes [1], consisting of 16 hadronic, 36 semi-hadronic and 24 leptonic processes, presented in a coherent and uniform environment. Flavor mixing is set to zero. The coupling

[1] In version v1.0, final states with top quarks or those obtained by complex conjugation are not explicitly included. For generating t-quark final state processes, the user may try to change the c-quark mass to the top mass together with an interchange $s \leftrightarrow b$, but the integration convergence is not warranted because $t \to bW$ is a real process contrary to $c \to sW$.

between electron and Higgs boson is suppressed. Once a process has been selected, the total and differential cross sections are computed with the Monte-Carlo integration package `BASES` [3]. Then `SPRING` [3], a general purpose event generator, provides unweighted events.

The matrix element generated by `GRACE` corresponds to the genuine tree level process. However, several corrections must be introduced to produce realistic cross sections. First of all the most basic correction, inherent to heavy boson production, is due to the finite width of the W or Z^0 boson to ensure a finite cross section. It should be noted that if one introduces the width in a naive way, it violates the gauge invariance and in some case may lead to a divergent cross-section. The $e^+e^- \to e^-\bar{\nu}_e q\bar{q}'$ cross section, for example, blows up at $\theta_e \approx 0$. To cure this problem, the terms which satisfy the Ward identity are properly subtracted from the electron current which is connected to the t-channel photon[4]. The computation of the constant and the running decay widths of $W^\pm$ and Z^0 is presented in the section 2.1.

Two additional effects, although of different origins, can be, in first approximation, introduced into any selected process; radiative corrections and hadronization of the final quarks.

For the radiative corrections two techniques are proposed in the program. The first one uses the well-known analytic form of $e^\pm$ structure function[5] and the second is based on `QEDPS`[6], a radiative correction generator producing an indefinite numbers of photons according to the parton shower algorithm in the leading-logarithmic (LL) approximation. Originally this algorithm has been developed to simulate QCD parton shower. One important point here is that `QEDPS` reproduces the radiative photon transverse momentum distributions. The details of these two methods shall be given in section 2.2. Final state radiation (FSR) for the electron and muon can also be generated with `QEDPS`. However the contribution of the interference between ISR and FSR is *not* yet included. Hence one should not use the FSR mode when the final state contains electron for kinematical regions where the t-channel photon exchange is the dominant diagram. The FSR for the quarks is not allowed in `grc4f`, because the QCD evolution scale is much shorter than the QED one, therefore the photonic correction on quarks might be meaningless. We recommend to use the FSR mode only for the case where the W-pair or Z-pair ($Z\gamma$) production diagrams are dominant.

We assume that the hadronization of partons can be separated from the hard interaction studied here. Under this assumption, the calculation of cross sections is exact in `grc4f`. Final state parton hadronization is performed, in `grc4f`, through the `LUND` mechanism as implemented in `JETSET`[7]. A set of color bases is defined to select final state color flow. Possible ambiguities in this procedure as well as other QCD related issues are discussed in details in section 2.3.

In order not to waste cpu time and disk space in the generation of events that will be eventually rejected by detector acceptance or threshold, a set of general cuts whose values can be set by the user have been implemented directly in the kinematics as presented in section 2.4.

The Coulomb correction[8] due to the exchange of a virtual photon between two intermediate W is important for non-relativistic W, namely close to the production threshold. It may reach 4% of the total cross-section. The introduction of this effect is described in section 2.5.

Anomalous couplings in the interaction among vector bosons is introduced in section 2.6.

The basic input parameters used in the program are listed hereafter. Fermion masses are taken from the report of Particle Data Group [9], but can be set to zero if necessary.

$$\begin{aligned} M_W &= 80.23 \text{ GeV}, \\ M_Z &= 91.1888 \text{ GeV}, \\ \Gamma_W &= 3G_F M_W^3/(\sqrt{8}\pi), \qquad G_F = 1.16639 \cdot 10^{-5} \text{ GeV}^{-2}, \end{aligned}$$

$$\begin{aligned} \Gamma_Z &= 2.497 \text{ GeV}, \\ \alpha(0) &= 1/137.036, \qquad \alpha(M_W) = 1/128.07, \\ \alpha_S &= 0.12. \end{aligned}$$

Here $\alpha(Q)$ is the QED fine structure constant at the energy scale Q and α_S is the QCD coupling. These values can be changed through control data. The weak mixing angle is calculated by $\sin^2\theta_W = 1 - M_W^2/M_Z^2$.

The matrix elements are given in term of helicity amplitudes, it is therefore possible to select any helicity state configuration (initial and final).

This paper is organized as follows. Theoretical details for the problems mentioned in the introduction will be given in section 2. The structure of the program is described in section 3. In section 4, all details about running the program are presented. Some improvement for future releases are summarized in the section 5. Three appendices present the parameters and options which can be changed by the user, the list of all processes and the program installation procedure followed by a run example.

2. Theoretical aspects

This section covers the treatment of the boson width, the introduction of the initial and final state radiation, the QCD related issues such as hadronization and the color problems, the description of kinematics and cuts, the Coulomb correction and the anomalous coupling of heavy vector bosons.

2.1 Gauge boson width

The $O(\alpha)$ self-energy of the gauge boson, $\Sigma^{(1)}(k^2)$, generally satisfies

$$\begin{aligned} \mathrm{Re}\Sigma^{(1)}(M^2) &= 0, \\ \mathrm{Im}\Sigma^{(1)}(M^2) &= -M\Gamma(M^2), \end{aligned}$$

where M is the mass of the gauge boson and $\Gamma(M^2)$ is the lowest order decay width. This induces the replacement of the gauge boson propagator by the following simple Breit-Wigner form:

$$\frac{1}{k^2 - M^2} \to \frac{1}{k^2 - M^2 + iM\Gamma(M^2)}$$

This form is used for the fixed width scheme in `grc4f` whenever the propagator appears with positive momentum squared.

Another way is to take into account the energy dependence of the self-energy. Based on the observation that the contribution of fermion pairs to $\mathrm{Im}\Sigma^{(1)}$ is k^2 times a constant in any gauge as long as all the light fermion masses are neglected, the following energy dependent width has been proposed [10].

$$M\Gamma(M^2) \to -\mathrm{Im}\Sigma^{(1)}(k^2)|_{\text{fermion pairs}} \cong \frac{k^2}{M}\Gamma(M^2).$$

In `grc4f` this form is used as the default, but the constant width can be selected as well.

As mentioned in the previous section, the introduction of the boson width may raise difficulties, particularly when the electron is scattered in the very forward direction. Such final

states usually come from the generation of the so-called single W or Z process. To get rid of the divergent cross section, we apply the following method.

With an arbitrary gauge parameter ξ the electron current can be written as:

$$\begin{aligned} l_\mu &= \bar{u}(p')\gamma^\nu u(p)[g_{\mu\nu} + (\xi - 1)k_\mu k_\nu/k^2], & (1)\\ &= \bar{u}(p')\gamma_\mu u(p), & (2) \end{aligned}$$

where $p_\mu(p'_\mu)$ is the four-momentum of the initial (final) electron and $k_\mu = p_\mu - p'_\mu$, the momentum of the virtual photon. After squaring the amplitude and averaging over spin states, the matrix element can be written as

$$M = L_{\mu\nu}T^{\mu\nu}, \tag{3}$$

with

$$L_{\mu\nu} = \overline{\sum_{spin}} l_\mu l^*_\nu = 2\left[p_\mu p'_\nu + p_\nu p'_\mu + \frac{k^2}{2}g_{\mu\nu}\right]. \tag{4}$$

Let's assume that $T_{\mu\nu}$ is gauge invariant. Then one can replace $L_{\mu\nu}$ by

$$L_{\mu\nu} \to L'_{\mu\nu} = 4p_\mu p_\nu + k^2 g_{\mu\nu}. \tag{5}$$

In this form the first term is responsible for the blow-up of the cross section. Thanks to the gauge invariance, one can further replace the vector p_μ by:

$$p_\mu \to P_\mu = p_\mu - (p_0/k_0)k_\mu. \tag{6}$$

By substituting P_μ in Eq.(5) and dropping k_μ, one gets the final form

$$L'_{\mu\nu} \to L''_{\mu\nu} = 4P_\mu P_\nu + k^2 g_{\mu\nu}. \tag{7}$$

It is known that a product of P with an arbitrary vector A, $P \cdot A$, can be expressed by a sum of terms proportional to either m_e^2, $1 - \cos\theta_e$ or $\sin\theta_e$. The part $T_{\mu\nu}$ is expressed in terms of some momenta which are to be contracted with P_μ or P_ν. Hence in the region $\theta_e \approx 0$, any product behaves effectively like k^2, because $1 - \cos\theta_e$ vanishes almost like k^2. If the current $L''_{\mu\nu}$ is used instead of the original one $L_{\mu\nu}$, the cross-section remains finite down to $\theta_e = 0$.

2.2 Radiative corrections

In the first approach, the simple electron structure function is used. The electron structure function at $O(\alpha^2)$ [5] which is to be convoluted to the cross section for a primary process is given by

$$\begin{aligned} D(x,s) &= \left[1 + \frac{3}{8}\beta + \left(\frac{9}{128} - \frac{\zeta(2)}{8}\right)\beta^2\right]\frac{\beta}{2}(1-x)^{\beta/2-1} \\ &\quad -\frac{\beta}{4}(1+x) - \frac{\beta^2}{32}\left[4(1+x)\ln(1-x) + \frac{1+3x^2}{1-x}\ln x + (5+x)\right], & (8)\\ \beta &= (2\alpha/\pi)(\ln(s/m_e^2) - 1), & (9) \end{aligned}$$

where s is the square of the total energy of the system and x is the momentum fraction of the electron. It should be noted that, when compared with the exact $O(\alpha)$ calculation, the radiative

corrected cross section obtained by this function does not contain the overall multiplying K-factor:

$$1 + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right) = 1.006480\cdots. \tag{10}$$

In `grc4f` this factor is missing both for the structure function mode and `QEDPS` mode. If necessary, the final result can be multiplied by this factor for better accuracy.

The QED Parton Shower approach, `QEDPS`, is primarily based on the fact that $D(x, Q^2)$ obeys the Altarelli-Parisi equation:

$$\frac{dD(x,Q^2)}{d\ln Q^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y} P_+(x/y) D(y, Q^2), \tag{11}$$

in the leading-log(LL) approximation [11]. This is equivalent to the following integral equation:

$$D(x,Q^2) = \Pi(Q^2, Q_s^2) D(x, Q_s^2) + \frac{\alpha}{2\pi}\int_{Q_s^2}^{Q^2} \frac{dK^2}{K^2}\Pi(Q^2, K^2)\int_x^{1-\epsilon}\frac{dy}{y}P(y)D(x/y, K^2), \tag{12}$$

where the small quantity ϵ will be specified later. In these equations $P(x)$ is the split function and $P_+(x)$ is that with regularization at $x = 1$. Q_s^2 is the initial value of Q^2. For simplicity the fine structure constant α is assumed not running with Q^2. The Sudakov factor Π is given by:

$$\Pi(Q^2, Q'^2) = \exp\left(-\frac{\alpha}{2\pi}\int_{Q'^2}^{Q^2}\frac{dK^2}{K^2}\int_0^{1-\epsilon} dx P(x)\right). \tag{13}$$

This is the probability that an electron evolves from Q'^2 to Q^2 without emitting hard photon. In other words, Π already contains the soft photon component, which causes the change in the electron virtuality, and the loop correction contribution at all orders of perturbation.

The integral form Eq.(12) can be solved by iteration. It is clear that the emission of n photons corresponds to n iterations. Hence it is possible to regard the process as a stochastic mechanism suggesting the following shower algorithm [12].

(a) Set $x_b = 1$. The variable x_b is the fraction of the light-cone momentum of the virtual electron that annihilates.

(b) Choose a random number η. If it is smaller than $\Pi(Q^2, Q_s^2)$, then the evolution stops. If not, one can find the virtuality K^2 that satisfies $\eta = \Pi(K^2, Q_s^2)$ at which a branching takes place.

(c) Fix x according to the probability $P(x)$ between 0 and $1 - \epsilon$. Then x_b is replaced by $x_b x$. Go back to (b) by substituting K^2 into Q_s^2 and repeat until the evolution stops.

Once a radiative process is fixed by this algorithm, each branching of a photon is a real process, that is, an electron with x, K^2 decays like:

$$e^-(x, -K^2) \to e^-(xy, -K'^2) + \gamma(x(1-y), Q_0^2). \tag{14}$$

Here we have introduced a cutoff Q_0^2 to avoid the infrared divergence. The momentum conservation at the branching gives: $-K^2 = -K'^2/y + Q_0^2/(1-y) + \mathbf{k}_T^2/(y(1-y))$ which in turn

determines the photon transverse momentum relative to the parent, $\mathbf{k}_T^2$, from y, K^2, K'^2. This technique gives the $\mathbf{k}_T^2$ distribution as well as the shape of x.

The kinematical boundary $y(K^2 + Q_0^2/(1-y)) \leq K'^2$, equivalent to $\mathbf{k}_T^2 > 0$, fixes ϵ as $\epsilon = Q_0^2/K'^2$ since $K^2 \ll K'^2$ is expected. In ref.[13] the important role played by this ϵ is discussed in more details.

The above description of the algorithm concerns the case where either e^- or e^+ radiates photons when the axial gauge vector is chosen along the momentum of the other electron, namely e^+ or e^-. In the program, however, we use the double cascade scheme to ensure the symmetry of the radiation between e^+ and e^- [14]. These two are mathematically equivalent in the LL approximation.

The two parameters Q_s^2 and Q_0^2 are given as follows;

$$Q_s^2 = m_e^2 e = m_e^2 \times 2.71828\cdots, \qquad Q_0^2 = 10^{-12} \ \ \mathrm{GeV}^2. \tag{15}$$

Q_s^2 is defined so as to include the constant term -1 of β in such a way that $\beta = (2\alpha/\pi)(\ln(s/m_e^2) - 1) = (2\alpha/\pi)\ln(s/(m_e^2 e))$. Since Q_0^2 is unphysical, any observable should not depend on it. It has been checked that increasing Q_0^2 up to $O(m_e^2/10)$ leaves the result unchanged within the statistical error of the event generation [6].

This scheme can be applied for the radiation from the final state charged particles as well. The lower bound of the virtuality integration, Q_s^2, is now the mass square of the final particle instead of the initial electron mass. The upper bound is the four-momentum squared of the lepton pair. Here we assume that the lepton-pairs are created from the gauge boson. The FSR should be used for the processes in which the W-pair or Z-pair ($Z\gamma$) production diagrams are dominating, but not for the processes such as multi-peripheral two-photon like diagrams.

2.3 QCD related issues

2.3.1 Color bases

We calculate the matrix element using `GRACE` which may be written as

$$M = |\sum T_j|^2. \tag{16}$$

Each amplitude T_j includes a color factor. The color indices of the external particle must be summed in the final state and averaged in the initial state.

If a diagram has four gluon vertices, the diagram is separated into three pieces, the so-called s-, t- and u-channels, respectively, for each vertex. Let's now consider the T_j's not as amplitude but as a component of an amplitude after this decomposition.

For each T_j, the color factor can be factorized out and expanded on a set of color bases, C_k:

$$T_j = \left(\sum_k w_j^{(k)} C_k\right) \tilde{T}_j \tag{17}$$

where $w_j^{(k)}$'s are numbers. Then the matrix element is given by

$$M = \sum_{k,k'} \left(C_k C_{k'}^\dagger\right) F_k F_{k'}^*, \qquad F_k = \sum_j w_j^{(k)} \tilde{T}_j \ . \tag{18}$$

Therefore, for the four-gluon vertices, the colored part of an amplitude consists of three-gluon vertices ($-if_{abc}$), quark-gluon vertices (t^a) and non-colored vertices. The ghost-gluon

vertex bears the same color structure as the three-gluon vertex and do not require a specific treatment.

The choice of the color bases and the technique used to introduce color flow at the event generation level are not all equivalent. Let's describe one of the simplest approach. The following algorithm has been introduced in `GRACE`.

1. We consider a process in which n_q quark pairs and n_g gluons exist among external particles. For any pair of amplitudes, T_j and $T_k^\dagger$, the color index of an external gluon is contracted between them. Making use of this, each gluon is converted into a pair of quark and antiquark creating a quark-gluon vertex. An overall factor 2^{n_g} is assigned to M from:

$$\delta^{ab} = \mathrm{Tr}\ t^a t^b / T_R, \qquad T_R = \frac{1}{2}. \tag{19}$$

2. External particles are n pairs of quarks and antiquarks where $n = n_q + n_g$. Quarks and antiquarks are denoted as $1, 2, 3, \ldots, n$ and $\bar{1}, \bar{2}, \bar{3}, \ldots, \bar{n}$, respectively. The color base here has the form:

$$C_k = \delta_{1 j_1} \delta_{2 j_2} \cdots \delta_{n j_n} \tag{20}$$

   where $j_1, j_2, \ldots, j_n$ is a permutation of $\bar{1}, \bar{2}, \bar{3}, \ldots, \bar{n}$. The number of color bases is hence $n!$.

3. Each three-gluon vertex is converted into a pair of quark loops by

$$-if_{abc} = (-\mathrm{Tr}\ t^a t^b t^c + \mathrm{Tr}\ t^b t^a t^c)/T_R. \tag{21}$$

4. Each gluon propagator is replaced by quark lines by use of the Fiertz transformation:

$$(t^a)_{ij} \delta^{ab} (t^b)_{kl} = -\frac{1}{2N_C} \delta_{ij} \delta_{kl} + \frac{1}{2} \delta_{il} \delta_{jk}, \quad (N_C = 3) \tag{22}$$

5. After the above procedures, only quark lines remain. For each closed quark loop, a factor $\mathrm{Tr}\ 1 = 3$ is assigned.

When the calculation is done in the covariant gauge, the diagrams including external ghost particles, if any, are to be considered separately[2].

A different approach can be followed without gluon-quark conversion. For example, let us denote quarks, antiquarks, and gluons as $1, 2, 3, \ldots, n_q$, $\bar{1}, \bar{2}, \bar{3}, \ldots, \bar{n}_q$, and $\hat{1}, \hat{2}, \hat{3}, \ldots, \hat{n}_g$, respectively. Instead of Eq.(20), the color bases can be represented by a product of the following objects,

$$\delta_{1 j_1}, \quad (t^{\hat{k_1}})_{1 j_1}, \quad (t^{\hat{k_1}} t^{\hat{k_2}})_{1 j_1}, \quad \ldots$$

where $j_1, j_2, \ldots$ and $k_1, k_2, \ldots$ are permutation of $\bar{1}, \bar{2}, \bar{3}, \ldots, \bar{n}_q$ and $\hat{1}, \hat{2}, \hat{3}, \ldots, \hat{n}_g$, respectively.

2.3.2 Interface to hadronization

As mentioned in the previous section, there are many possible choice for selecting a color base. As far as the total cross section is concerned they give the same result. However, the choice of the color base and the technique used to introduce color flow at the generation level are not equivalent and may induce noticeable discrepancies after hadronization.

[2]This does not happen in `grc4f`.

We take the string picture used in JETSET as a concrete example of hadronization. The color flow pattern can be assigned to each color base intuitively. However, an event is generated by matrix element which is the square of the amplitude, i.e., a linear combination of color bases. For interference terms, assignment of a color flow pattern is ambiguous. One possible solution is to introduce a set of orthogonal bases.

To illustrate this point, we consider the four-quark final state, $q_1\bar{q}_2q_3\bar{q}_4$ which is produced by grc4f. We label them 1, 2, 3, and 4. Among possible candidates, let us consider the following three types of color bases.

1. Primitive base
$$\begin{cases} C_1 &= \delta_{12}\delta_{34} \\ C_2 &= \delta_{14}\delta_{32} \end{cases} \tag{23}$$

2. Orthogonal base
$$\begin{cases} C_1^{(o)} &= C_1 + C_2 \\ C_2^{(o)} &= C_1 - C_2 \end{cases} \tag{24}$$

3. Extended orthogonal base
$$\begin{cases} C_1^{(e)} &= C_1 - \delta_{1234} \\ C_2^{(e)} &= C_2 - \delta_{1234} \\ C_3^{(e)} &= \delta_{1234} \end{cases} \tag{25}$$

Here $\delta_{1234} = 1$ only when all four indices are equal and $= 0$ otherwise.

For each primitive base, one can assign a configuration of two strings naturally. They are, however, not diagonal; the interpretation of interference term is obscure. In the second case, the orthogonal bases, there is no interference term. However, each base $C_k^{(o)}$ do not relate directly to the string picture and each $C_k^{(o)}$ contains $|C_1|^2$ and $|C_2|^2$ with equal weight. The same thing happens in elementary quantum mechanics: The information on left/right circular polarization is lost after the light goes through a linear polarization filter. In the third example, the first two $C_k^{(e)}$ can be assigned to two strings of different colors. The third one is a kind of 4-quark loop worm. They are orthogonal to each other but they do not fit well with the JETSET approach.

The situation does not change for the case with more external particles, and for both cases with or without the gluon conversion. We have to say that there is some *distance* between the color bases and the definition of color singlet sub-system (e.g., strings) in the hadronization model.

In the present scheme of grc4f, we use the primitive base case and the color flow is chosen for each event stochastically with weight $C_kC_k^\dagger|F_k|^2$.

2.3.3 Options

There is an option to include the overall QCD correction factor. Here the cross section is multiplied by a simple factor $(1 + \alpha_S/\pi)$ for each quark vertex.

When the final state is a four-quark state, gluon exchange diagrams are included. It is possible to remove these by setting control data.

2.4 Kinematics and cuts

In the phase-space integration by the adaptive Monte Carlo method, a proper treatment of the following singuler behavior of the amplitude is necessary;

1. s-channel W, Z resonances and γ propagators.

2. t-channel electron and electron neutrino propagators in Z-pair ($Z\gamma$, $\gamma\gamma$) production and in W-pair production.

3. The electron (positron) forward dcattering of the two-photon processes.

4. Mixed resonance of W-pair and Z-pair ($Z\gamma$, $\gamma\gamma$) processes, such as $ud\bar{d}\bar{u}d$ process.

5. Identical particles in the final state, such as $\mu^+\mu^-\mu^+\mu^-$.

`grc4f` includes the mapping routine from eight integration variables to the four-momenta of final particles with proper treatment of these singuler behavior. The forward scattering of the two-photon processes are not fully treated. Higgs boson diagrams are included in the amplitude, however the kinematics does not treat the Higgs boson resonance yet. (For cross section with very forward electrons or with Higgs boson resonance, contact the authors [3].) For the identical particles in the final state, some momentum ordering is assumed in the kinematics routine, then, for instance, the first particle has always larger momentum than the second particle.

One can apply some experimental cuts for the phase space integration; energy and angle cuts on all final particles and a invariant-mass cut on any pair of final particles. These parameters can be modified by the user. For comparison with other programs, `grc4f` has the `canonical cut` option used in ref.[15], which is;

1. the energy of charged leptons must be greater than 1 GeV.

2. the polar angle of charged leptons must be between 10 and 170 degree.

3. the energy of quarks must be greater than 3 GeV.

4. the opening angle between charged leptons and quarks must be greater than 5 degree.

5. the invariant mass of quark pairs must be greater than 5 GeV.

Here the 'charged leptons' include τ's too.

2.5 Coulomb correction

This effect has been originally discussed for the *off-shell* W-pair production[8] corresponding to the three resonant diagrams. The set of these diagrams cannot satisfy the gauge invariance and has no physical meaning in principle. In `grc4f`, however, all relevant diagrams are taken into account and the gauge invariance is restored from the contribution of the non-resonant diagrams (besides an effect from the finite width of W boson). To maintain the invariance we adopt the following prescription: *the Coulomb factor is multiplied to the minimum set of gauge invariant diagrams containing the W-pair production*[15]. Hence the Coulomb multiplicative factor appears in some diagrams even without W-pair. The following formula is used:

$$\sigma_{Coul} = \sigma_{gauge\ inv.}\frac{\alpha\pi}{2\bar{\beta}}\left[1-\frac{2}{\pi}\arctan\left(\frac{|\beta_M+\Delta|^2-\bar{\beta}}{2\bar{\beta}\mathrm{Im}\beta_M}\right)\right],$$

[3] E-mail address:`grc4f@minami.kek.jp`

where

$$\begin{aligned}\bar{\beta} &= \frac{1}{s}\sqrt{s^2-2s(k_+^2+k_-^2)+(k_+^2-k_-^2)^2},\\ \beta_M &= \sqrt{1-4M^2/s}, \quad M^2=M_W^2-iM_W\Gamma_W, \quad \Delta=\frac{|k_+^2-k_-^2|}{s},\end{aligned}$$

and $-\pi/2 < \arctan y < \pi/2$. Here $\bar{\beta}$ is the average velocity of the W boson in *its center-of-mass system*. Two squared momentum k_+^2 and k_-^2 are the virtualities of the intermediate W bosons.

2.6 Anomalous coupling

In the program, the anomalous coupling of heavy boson is available for the convenience of the user who may be interested to see the result of an *ad hoc* standard model extension, although there is no definite and reliable model beyond the standard model at present. The program includes only those terms which conserve C and P invariance which correspond to the following effective Lagrangian[16];

$$\begin{aligned}L_{eff} &= -ig_V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) - ig_V\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} - ig_V\frac{\lambda_V}{m_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu V^{\lambda\nu},\\ W_{\mu\nu} &= \partial_\mu W_\nu - \partial_\nu W_\mu, \quad V_{\mu\nu}=\partial_\mu V_\nu-\partial_\nu V_\mu, \quad V=Z^0 \text{ or } \gamma, \quad g_V=\begin{cases}-e & V=\gamma\\ -e\cot\theta_W & V=Z^0\end{cases}\end{aligned}$$

Here κ_V and λ_V stand for the anomalous couplings, which takes 1 and 0, respectively, in the standard model. Deviation from these values corresponds to the introduction of anomalous coupling with arbitrary strength.

3. Structure of the program

The generator `grc4f` enables us to generate any $e^+e^- \to$ 4-fermions events with or without radiative corrections. This requires different calculation in some part of the program. In addition there are many options covering theoretical and experimental requirements. Since all program components are distributed as source code, users can set all options by editing the relevant subprograms directly. However, an interface program `grc4f` has been created to lighten the user's burden. It selects and/or corrects the components which are affected by the various options and create a "Makefile" according to the user requirements. This procedure is called the source generation phase.

In the integration step, the matrix element of a selected process is integrated over the phase space by the subprogram `BASES`, which gives the effective total and differential cross sections and the probability distribution used in event generation phase. There, the subprogram `SPRING` samples a point in the phase space and test if it can be accepted as a new event according to its probability. When an event is accepted the program control returns from `SPRING` to the main program, where further analysis is performed by using the resultant four-momenta of the final state particles.

There are therefore, three steps in the generator `grc4f`, the first is the source generation, the second is the integration, and the third is the event generation.
In addition to the user interface program `grc4f`, the following programs are available in the `grc4f` package:

i) The main programs MAINBS and MAINSP, and all program components for the integration and event generation steps.

ii) The interface programs to CERNLIB (GRC2CL) and to JETSET (GRC2SH).

iii) 76 function programs FUNCs for processes $e^+e^- \to$ 4-fermions, each of which calculates the numerical value of the differential cross section for each process.

iv) The kinematics subprograms KINMOQ and KINEMO for the processes with radiative correction using the QED parton shower model or the electron structure function, respectively.

v) The library CHANEL[2] used to calculate the numerical values of basic components of Feynman diagrams in terms of helicity amplitudes.

vi) The numerical integration and event generation program package BASES/SPRING v5.1[3].

The relationship among these program components and their function are presented in the next two sections.

3.1 Source generation step

The user interface program grc4f reads the parameters from control data prepared by users, which contains process selection, type of radiative corrections, physical options, experimental cuts, etc., and generates all necessary components:

i) A main program MAINBS for the integration.

ii) Interface programs GRC2CL and GRC2SH.

iii) Three initialization subprograms USRPRM, MODMAS and KINIT, and

iv) a "Makefile".

3.2 Integration step

Before starting the numerical integration the main program MAINBS invokes an initialization subprogram USERIN, where the following subprograms are called in this order:

USRPRM	:	To define the set of so-called "canonical cut" [15] authorized by LEP200 working group and some additional optional parameters.
SETMAS	:	To set masses and decay widths of particles.
MODMAS	:	To alter the default values of all parameters defined in SETMAS.
AMPARM	:	To set the coupling constants and others parameters.
KINIT	:	To set the parameters for the integration, kinematics, cuts, histograms etc.

The subprograms SETMAS and AMPARM are generated by the GRACE system. There are no consistency checks among the constants, e.g. M_Z, M_W and $\sin\theta_W$, so all modifications on these parameters in the subprograms USRPRM, MODMAS and KINIT are under the user responsibility alone.

The integration program BASES calculates the scattering cross section by sampling the function FUNC on the allowed phase space segmented by an self adapted grid where finer cells are

clustered on the high gradient zones. This is an iterative process running until either the maximum number of allowed iteration is reached or the required accuracy is obtained. In the function `FUNC`, the kinematics subroutine `KINEMO` or `KINMOQ` is used to map the integral variables with the four-momenta of the final state particles. `KINEMO` is used for reaction with no radiative corrections or those involving initial radiation treated with the structure function techniques. `KINMOQ` is called for processes where radiative corrections are computed with the QED parton shower method. The subprograms `AMPTBL` and `AMPSUM` are further called for calculating the helicity amplitudes and the sum of the matrix element squared.

It is recommended to look at the integration result carefully, especially over the convergency behaviors both for the grid optimization and integration steps. When the accuracy of each iteration fluctuates, iteration by iteration, and, in some case, it may jump up suddenly to a large value compared to the other iterations, the resultant estimate of integral may not be reliable. There are two possible origins of this behavior; too few sampling points or/and an unsuitable choice of the kinematics.

After the numerical integration by `BASES`, the subprograms `BSINFO` and `BHPLOT` are called to print the result of integration and the histograms, respectively. Before terminating the integration procedure the probability distribution obtained by the integration can be saved in a file by invoking `BSWRIT`, which is then used for the event generation by `SPRING`.

3.3 Event generation step

After integrating the differential cross section and saving the probability distribution, the main program, `MAINSP`, handles the event generation program. The subprogram `BSREAD` is invoked to restore the probability distribution and then the subprogram `USERIN` is called. Each call to `SPRING` generates one event by sampling a point in the phase volume. It then calculates the differential cross section at that point using the same function `FUNC` seen in the integration phase. Using the usual unweighting technique, this event is accepted or rejected. When an event is generated, `SPRING` returns particle identification and four momenta. The event information is stored in the labelled common `LUJETS` by calling subprogram `SP2LND`. Here, the information for the color connection to be referred by `JETSET` is also supplied. Among the final states in Appendix B, those in Table 3 have non-trivial color flow which is determined as is described in the section 2.3.

Then parton shower and hadronization of quarks and gluons can be performed by calling `LUSHOW` and `LUEXEC`. At the end of the event generation, the routine `SPINFO` and `SHPLOT` are invoked successively for printing event generation and histograms.

4. How to run the program

The user should first prepare control data to define the process, options and parameters for experimental cuts etc. The user interface program `grc4f` takes this control data (let's call it `control.data`) as an input.

```
process  =  eNEuD
energy   =  190.0d0
canon    =  yes
type     =  tree
massive  =  yes
coulomb  =  no
anomal   =  no
qcdcr    =  no
end
```

The first line specifies the process to be calculated and the second is the center of mass energy in GeV unit. The others are options, whose meanings are given in Appendix A. Then the user may type:

```
% grc4f < control.data
```

If the message "syntax error" is returned, no files will be generated and the contents of the control data file must carefully be checked. After a successful completion, the following messages should be returned:

```
Process is "eNEuD"
Energy is "190.0d0"
CANON <yes>
MASSIV <yes>
COULMB <no>
ANOMAL <no>
QCDCR <no>
bye-bye
absolute directory name is /home/grc4f/prc/elNEuqDQ
-----------------------------------------
cd /home/grc4f/prc/elNEuqDQ
make
integ
spring
-----------------------------------------
```

According to the parameters given in control data, the files, i.e. *usrprm.f*, *modmas.f*, *kinit.f*, *mainbs.f*, *mainsp.f* and *Makefile*, are generated in a specified subdirectory (`elNEuqDQ` in this case).
According to the last four lines in the message, users can proceed the calculations as follows:

i) Change directory by

   ```
   % cd /home/grc4f/prc/elNEuqUD
   ```

ii) Create an executable `integ` for the integration by typing:

   ```
   % make integ
   ```

iii) Numerical integration is actually performed by typing:

```
% integ
```

The results of integration step are displayed as well as written in an output file `bases.result`. The total cross section in *pb* with the error are displayed at the last row, under `Cumulative Result`, in the table of the `Convergence Behavior for the Integration step`. The differential cross sections as a function of the energy and angle of each particle and invariant masses of any two final particles will also be printed. The probability distribution is written in a file `bases.data` which will be used in the event generation step by `spring`.

iv) Before running the event generation, users should edit `mainsp.f` to set additional parameters like the number of events and call user's own analysis routines.

The following is the structure of the generated `mainsp.f`, where four-momenta of all particles are stored in the common/lujets/ in the `JETSET` format by calling subprogram `sp2lnd` in the event-loop:

```
      implicit real*8(a-h,o-z)
       .....................
      real*4  p,v
      common/lujets/n,k(4000,5),p(4000,5),v(4000,5)
       .....................
      mxtry  = 50
      mxevnt = 10000
       .....................
      do 100 nevnt = 1, mxevnt

         call spring( func, mxtry )
       .....................
*        -----------------
          call sp2lnd
*        -----------------
*
*       ================================
*       (   user_analysis   )
*       ================================
*
  100 continue
       .....................
      stop
      end
```

v) Create an executable `spring` for event generation by typing:

```
% make spring
```

vi) Start the event generation by typing:

```
% spring
```

Information of the event generation will be written in the `spring.result` file. Users should pay special attention to the histograms. The distributions of generated events are superimposed by "0" on the original histograms by `BASES`. These two distributions should be consistent within the statistical error of the generation. For the detail of the output files of `BASES` and `SPRING`, user can consult the Ref.[3].

5. Summary

The generator `grc4f` enables us to calculate the effective cross section and to generate events for one of 76 $e^+e^- \to$ 4-fermions processes listed in appendix B. It is dedicated to the LEP and future linear collider physics studies. The produced quarks can be hadronized according to `JETSET`. Also processes with initial and final radiations can be generated in terms of the electron structure function or the QED parton shower methods, though the inclusion of the interference between the initial and final radiations requires further study.

There still remain important problems to be solved and further necessary improvements. Among them it will be desirable to extend the program so as to produce several final state processes in a single run like $e^+e^- \to$ 4-quarks. In order to get more precise QED corrections an implementation of a complete next-to-leading logarithmic effects[17] is unavoidable.

In this version, we have assumed that the hadronization of partons takes place independent of the hard interaction which produces partons. However a very important contribution arises from diagram where a gluon is exchanged between quarks produced in the two W decays. Taking into account this effect implies higher order calculations or the implementation of a specific phenomenologic correction[15].

Finally the present version provides only 76 processes, the missing processes will be prepared soon by using `GRACE`.

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Appendix A. Option table in Control data

In the table below, the default values are underlined and the relation between commands and variable/array in Fortran sources is also described. Variable names are written in bold letters and file names in italic.

i) Process selection.

`Process`	=	`eNEuD` abbreviation of process name

This specifies the subdirectory name, where the necessary function program to calculate matrix elements are stored. Tables 1, 2, and 3 in Appendix B shows the abbreviation of process names and the subdirectory names where they are stored are listed.

ii) Center of mass energy.

`energy`	=	`190.d0` CMS energy in GeV `w` in *kinit.f*

iii) Global options

`helicity1`	=	`average`, `left`, `right` Helicity state for the initial electron.
`helicity2`	=	`average`, `left`, `right` Helicity state for the initial positron.
`helicity3`	=	`sum`, `left`, `right` Helicity state for 3rd particle.
`helicity4`	=	`sum`, `left`, `right` Helicity state for 4th particle.
`helicity5`	=	`sum`, `left`, `right` Helicity state for 5th particle.
`helicity6`	=	`sum`, `left`, `right` Helicity state for 6th particle.

`type`	=	`tree`, `sf`, `qedpsi`, `qedpsif` Type of calculation: Without radiation(`tree`), ISR with structure function(`sf`), ISR with QEDPS(`qedpsi`) and ISR and FSR with QEDPS(`qedpsif`). `jqedps = 0`, `isr = 0` without radiation(`tree`). `jqedps = 0`, `isr = 1` for `sf`. `jqedps = 1`, `ips = 1` for `qedpsi`. `jqedps = 1`, `ips = 2` for `qedpsif`. `jqedps` in *usrprm.f*, `isr` and `ips` in *kinit.f*.

`canon`	=	`yes`, `no` Apply canonical cuts or not: `jcanon = 1` or `0` in *usrprm.f.*
`massiv`	=	`yes`, `no` Quarks are massive or massless: `jqmass = 1 or 0` in *usrprm.f.*
`width`	=	`run`, `fixed` Running width or fixed width: `jwidth = 0` or `1` in *usrprm.f.*

iv) Physical options

`coulomb`	=	`yes`, `no` Coulomb correction: `jcolmb = 1` or `0` in *modmas.f.*
`qcdcr`	=	`yes`, `no` Include overall QCD correction factor: `jqcdcr = 1` or `0` in *modmas.f.*
`gluon`	=	`yes`, `no` Include diagrams with gluon exchange: `jgluon = 1` or `0` in *modmas.f.*

`anomal`	=	`yes`, `no` `jano3v = 1` or `0` in *modmas.f.* Anomalous coupling:
`ankaa`	=	`1.0d0` κ_γ.
`anlma`	=	`0.0d0` λ_γ.
`ankaz`	=	`1.0d0` κ_{Z^0}.
`anlmz`	=	`0.0d0` λ_{Z^0}. See section 2.6 for the definition of above variables. if "`anomalous = no`" is specified, these options affect nothing.

v) Masses, widths and α (only if "`canon = no`").

`amw`	=	80.23D0 W mass in GeV: `amw` in *modmas.f.*
`agw`	=	2.03367033062746D0 W width in GeV:`agw` in *modmas.f.*
`amz`	=	91.1888D0 Z mass in GeV: `amz` in *modmas.f.*
`agz`	=	2.4974D0 Z width in GeV: `agz` in *modmas.f.*
`alphai`	=	128.07D0 α^{-1}:`alphai` in *modmas.f.*
`alpha_s`	=	0.12D0 α_s:`alpha_s` in *modmas.f.*

vi) Experimental cuts (only if "`canon = no`").

The numbering convention of particles follows the `GRACE` scheme, where the initial electron and positron are 1st and 2nd, respectively, and the four final particles are numbered 3, 4, 5, 6. In the process name of Table 1, 2, and 3, the order of particles corresponds to this numbering convention. For instance, in the process, $e^-\bar{\nu}_e u\bar{d}$, the 3rd is e^-, the 4th is $\bar{\nu}_e$, the 5th is u and the 6th is $\bar{d}$.

`thecut3`	=	180.d0,0.0d0 Angle cut for 3rd particle in degree (backward-angle,forward-angle). `coscut(1:2,1)=cos(thecut3)` in *kinit.f.*
`thecut4`	=	180.d0,0.0d0 Angle cut for 4th particle in degree (backward-angle,forward-angle). `coscut(1:2,2)=cos(thecut4)` in *kinit.f.*
`thecut5`	=	180.d0,0.0d0 Angle cut for 5th particle in degree (backward-angle,forward-angle). `coscut(1:2,3)=cos(thecut5)` in *kinit.f.*
`thecut6`	=	180.d0,0.0d0 Angle cut for 6th particle in degree (backward-angle,forward-angle). `coscut(1:2,4)=cos(thecut6)` in *kinit.f.*

Instead of giving a numerical value, the user can use the keywords as below: `amass1(`i`)` has the mass for i-th particle and `w` is the CM energy.

`engcut3`	=	`amass1(3),w` Energy cut for 3rd particle (min.,max.) `engyct(1:2,1)` in *kinit.f*
`engcut4`	=	`amass1(4),w` Energy cut for 4th particle (min.,max.) `engyct(1:2,2)` in *kinit.f*
`engcut5`	=	`amass1(5),w` Energy cut for 5th particle (min.,max.) `engyct(1:2,3)` in *kinit.f*
`engcut6`	=	`amass1(6),w` Energy cut for 6th particle (min.,max.) `engyct(1:2,4)` in *kinit.f*

`ivmcut34`	=	`amass1(3)+amass1(4), w-(amass1(5)+amass1(6))` Invariant mass cut for 3-4 particles(min.,max.) `amasct(1:2,1)` in *kinit.f*
`ivmcut56`	=	`amass1(5)+amass1(6), w-(amass1(3)+amass1(4))` Invariant mass cut for 5-6 particles(min.,max.) `amasct(1:2,2)` in *kinit.f*
`ivmcut35`	=	`amass1(3)+amass1(5), w-(amass1(4)+amass1(6))` Invariant mass cut for 3-5 particles(min.,max.) `amasct(1:2,3)` in *kinit.f*

`ivmcut46`	=	`amass1(4)+amass1(6), w-(amass1(3)+amass1(5))` Invariant mass cut for 4-6 particles(min.,max.) `amasct(1:2,4)` in *kinit.f*
`ivmcut36`	=	`amass1(3)+amass1(6), w-(amass1(4)+amass1(5))` Invariant mass cut for 3-6 particles(min.,max.) `amasct(1:2,5)` in *kinit.f*
`ivmcut45`	=	`amass1(4)+amass1(5), w-(amass1(3)+amass1(6))` Invariant mass cut for 4-5 particles(min.,max.) `amasct(1:2,6)` in *kinit.f*

vii) Parameters for integration.

`itmx`	=	`7, 15` Iteration numbers: `itmx1`, `itmx2` in *kinit.f*
`acc`	=	`0.1, 0.05` Accuracies in %:`acc1`, `acc2` in *kinit.f*
`ncall`	=	`40000` Sampling points: `ncall` in *kinit.f*

viii) Parameters for event generation.

`mxtry`	=	50 Maximum trial numbers: `mxtry` in *mainsp.f*
`mxevnt`	=	10000 Maximum event numbers: `mxevnt` in *mainsp.f*
`hadron`	=	yes, no Hadronization with `JETSET`[7] for event generation: If `yes`, then a statement, `call luexec` is added in *mainsp.f*. In this case, program `JETSET` is necessary, and one should specify `JETSET` file location in this control data.
`jetset`	=	`/home/jetset/jetset74.o` Object file name for `JETSET`, if `hadron = yes`
`qcd_shower`	=	yes, no QCD parton shower with `JETSET`[7] for event generation: If `yes`, then a statement, `call lushow` is added in *mainsp.f*. In this case, program `JETSET` is necessary, and one should specify `JETSET` file location in this control data.

Those parameters affect *Makefile*.

ix) HBOOK interface.

`cernlib`	=	yes, no If `yes`, then the *bases.hbook* in integration and *spring.hbook* in event generation will be generated.

Those parameters affect *mainbs.f*, *mainsp.f* and *Makefile*.

x) End of description.

```
end
```

After the command `end` any command is neglected.

Appendix B. Process table

Here, the 76 processes included in `grc4f` are listed. In the heading, 'abbrev.' and 'dir.' stand for the abbreviated name used in the control card and directory name where the generated code is stored, respectively.

process	abbrev.	dir.	process	abbrev.	dir.
$e^-\bar{\nu}_e e^+\nu_e$	eNEEne	elELneNE	$e^-\bar{\nu}_e\nu_\mu\mu^+$	eNEnmMU	elNEMUnm
$e^-\bar{\nu}_e\nu_\tau\tau^+$	eNEntTAU	elNETAnt	$\mu^-\mu^+\nu_\mu\bar{\nu}_\mu$	muMUnmNM	muMUnmNM
$\tau^-\tau^+\nu_\tau\bar{\nu}_\tau$	tauTAUntNt	taTAntNT	$\mu^-\bar{\nu}_\mu\tau^+\nu_\tau$	muNMTAUnt	muNMTAta
$e^-e^+e^-e^+$	eEeE	elELelEL	$e^-e^+\mu^-\mu^+$	eEmuMU	elELmuMU
$e^-e^+\tau^-\tau^+$	eEtauTAU	elELtaTA	$\mu^-\mu^+\mu^-\mu^+$	muMUmuMU	muMUmuMU
$\tau^-\tau^+\tau^-\tau^+$	tauTAUtauTAU	taTAtaTA	$\mu^-\mu^+\tau^-\tau^+$	muMUtauTAU	muMUtaTA
$e^-e^+\nu_\mu\bar{\nu}_\mu$	eEnmNM	elELnmNM	$e^-e^+\nu_\tau\bar{\nu}_\tau$	eEntNT	elELntNT
$\nu_e\bar{\nu}_e\mu^-\mu^+$	neNEmuMU	neNEmuMU	$\nu_e\bar{\nu}_e\tau^-\tau^+$	neNEtauTAU	neNEtaTA
$\nu_\tau\bar{\nu}_\tau\mu^-\mu^+$	ntNTmuMU	ntNTmuMU	$\nu_\mu\bar{\nu}_\mu\tau^-\tau^+$	nmNMtauTAU	nmNMtaTA
$\nu_e\bar{\nu}_e\nu_e\bar{\nu}_e$	neNEneNE	neNEneNE	$\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$	neNEnmNM	neNEnmNM
$\nu_e\bar{\nu}_e\nu_\tau\bar{\nu}_\tau$	neNEntNT	neNEntNT	$\nu_\mu\bar{\nu}_\mu\nu_\mu\bar{\nu}_\mu$	nmNMnmNM	nmNMnmNM
$\nu_\tau\bar{\nu}_\tau\nu_\tau\bar{\nu}_\tau$	ntNTntNT	ntNTntNT	$\nu_\tau\bar{\nu}_\tau\nu_\mu\bar{\nu}_\mu$	nmNMntNT	ntNTnmNM

Table 1 Leptonic processes in grc4f.

process	abbrev.	dir.	process	abbrev.	dir.
$e^-\bar{\nu}_e u\bar{d}$	eNEuD	elNEuqDQ	$e^-\bar{\nu}_e c\bar{s}$	eNEcS	elNEcqSQ
$\mu^-\bar{\nu}_\mu u\bar{d}$	muNMuD	muNMuqDQ	$\mu^-\bar{\nu}_\mu c\bar{s}$	muNMcS	muNMcqSQ
$\tau^-\bar{\nu}_\tau u\bar{d}$	tauNTuD	taNTuqDQ	$\tau^-\bar{\nu}_\tau c\bar{s}$	tauNTcS	taNTcqSQ
$e^-e^+u\bar{u}$	eEuU	elELuqUQ	$e^-e^+c\bar{c}$	eEcC	elELcqCQ
$e^-e^+d\bar{d}$	eEdD	elELdqDQ	$e^-e^+s\bar{s}$	eEsS	elELsqSQ
$e^-e^+b\bar{b}$	eEbB	elELbqBQ	$\mu^-\mu^+u\bar{u}$	muMUuU	muMUuqUQ
$\mu^-\mu^+c\bar{c}$	muMUcC	muMUcqCQ	$\tau^-\tau^+u\bar{u}$	tauTAUuU	taTAuqUQ
$\tau^-\tau^+c\bar{c}$	tauTAUcC	taTAcqCQ	$\mu^-\mu^+d\bar{d}$	muMUdD	muMUdqDQ
$\mu^-\mu^+s\bar{s}$	muMUsS	muMUsqSQ	$\mu^-\mu^+b\bar{b}$	muMUbB	muMUbqBQ
$\tau^-\tau^+d\bar{d}$	tauTAUdD	taTAdqDQ	$\tau^-\tau^+s\bar{s}$	tauTAUsS	taTAsqSQ
$\tau^-\tau^+b\bar{b}$	tauTAUbB	taTAbqBQ	$\nu_e\bar{\nu}_e u\bar{u}$	neNEuU	neNEuqUQ
$\nu_e\bar{\nu}_e c\bar{c}$	neNEcC	neNEcqCQ	$\nu_e\bar{\nu}_e d\bar{d}$	neNEdD	neNEdqDQ
$\nu_e\bar{\nu}_e s\bar{s}$	neNEsS	neNEsqSQ	$\nu_e\bar{\nu}_e b\bar{b}$	neNEbB	neNEbqBQ
$\nu_\mu\bar{\nu}_\mu u\bar{u}$	nmNMuU	nmNMuqUQ	$\nu_\mu\bar{\nu}_\mu c\bar{c}$	nmNMcC	nmNMcqCQ
$\nu_\tau\bar{\nu}_\tau u\bar{u}$	ntNTuU	ntNTuqUQ	$\nu_\tau\bar{\nu}_\tau c\bar{c}$	ntNTcC	ntNTcqCQ
$\nu_\mu\bar{\nu}_\mu d\bar{d}$	nmNMdD	nmNMdqDQ	$\nu_\mu\bar{\nu}_\mu s\bar{s}$	nmNMsS	nmNMsqSQ
$\nu_\mu\bar{\nu}_\mu b\bar{b}$	nmNMbB	nmNMbqBQ	$\nu_\tau\bar{\nu}_\tau d\bar{d}$	ntNTdD	ntNTdqDQ
$\nu_\tau\bar{\nu}_\tau s\bar{s}$	ntNTsS	ntNTsqSQ	$\nu_\tau\bar{\nu}_\tau b\bar{b}$	ntNTbB	ntNTbqBQ

Table 2 Semi-hadronic processes in grc4f.

process	abbrev.	dir.	process	abbrev.	dir.
$u\bar{d}d\bar{u}$	uDUd	uqDQdqUQ	$c\bar{s}s\bar{c}$	cCSs	cqSQsqCQ
$u\bar{d}s\bar{c}$	uDsC	uqDQsqCQ	$u\bar{u}u\bar{u}$	uUuU	uqUQuqUQ
$c\bar{c}c\bar{c}$	cCcC	cqCQcqCQ	$d\bar{d}d\bar{d}$	dDdD	dqDQdqDQ
$s\bar{s}s\bar{s}$	sSsS	sqSQsqSQ	$b\bar{b}b\bar{b}$	bBbB	bqBQbqBQ
$u\bar{u}c\bar{c}$	uUcC	uqUQcqCQ	$u\bar{u}s\bar{s}$	uUsS	uqUQsqSQ
$u\bar{u}b\bar{b}$	uUbB	uqUQbqBQ	$c\bar{c}d\bar{d}$	cCdD	cqCQdqDQ
$c\bar{c}b\bar{b}$	cCbB	cqCQbqBQ	$d\bar{d}s\bar{s}$	dDsS	dqDQsqSQ
$d\bar{d}b\bar{b}$	dDbB	dqDQbqBQ	$s\bar{s}b\bar{b}$	sSbB	sqSQbqBQ

Table 3 Hadronic processes in `grc4f`.

Appendix C. Installation

The source code is available by `anonymous ftp` from `ftp.kek.jp` in the directory `kek/minami/grc4f`. The `grc4f` package contains the complete set of Fortran sources for 76 processes, the three libraries, i.e., `BASES/SPRING`, `CHANEL` and utilities for kinematics. Those source codes are written in FORTRAN77. In addition, `grc4f` provides the interface program to generate a few Fortran source files according to the control data specified by the user. This program is written in C, YACC and LEX. `grc4f` has been developed on HP-UX, but should run on any UNIX platform with a fortran complier.

The procedure of installation is as follows:

1. Editing *Makefile*.

   The following macros in *Makefile* should be taken care of by users themselves. For example, in the right hand side of `GRC4FDIR` the directory name where `grc4f` is installed should be given, and for `FC` and `FOPT` the relevant compiler name and option for your system should be given. The other macros can be left as they are.

`GRC4FDIR`	=	directory where `grc4f` are installed.
`PRCDIR`	=	directory where process files are installed. (default is `$(GRC4FDIR)/prc`.)
`LIBDIR`	=	directory where libraries are installed. (default is `$(GRC4FDIR)/lib`.)
`BINDIR`	=	directory where an executable is installed. (default is `$(GRC4FDIR)/bin`.)
`MACHINE`	=	`[hpux|hiux|sgi|dec|sun]`
`FC`	=	FORTRAN compiler command name.
`FOPT`	=	FORTRAN compiler options.

2. Compilation.

   By executing command `make install` one executable, i.e. the interface program(`grc4f`), is generated at `BINDIR`. Furthermore three libraries, i.e. `BASES/SPRING`, `CHANEL` and kinematics utility library, are generated in `LIBDIR`.

3. Install default *Makefile*s.

   By executing `src/lgen.sh` command, all *Makefile*s for 76 processes will be generated according to the environment where `grc4f` has been installed.

The sample control data files will be found at the directory `sample`.

TEST RUN OUTPUT

```
control data

process = eNEuD
end
```

Followings are the output files from `BASES` and `SPRING`. Only one histogram, the energy distribution of the particle 1, is shown since the whole output is too lengthy to be included here.

```
**********************************************************************
*-------------------------------------------------444--------########-*
*-------------------------------------------------44444-------###----##-*
*---######---------##--##------#####----------444--44----##########---*
*-####---#######--##########--####---###------444----44-------###-------*
*-###------##------###------###------##----44444444444444----###-------*
*--##########------###------###------------44444444444444----###-------*
*-####------------###------#######---###------------44-------###-------*
*-#############--#######------########--------------44----#########----*
*-##--------###-------------------------------------------------------*
*-############-------------------------------------------------------*
*---------------------------------------------- GRACE INSIDE ------*
**********************************************************************
*                      Version 1.0 (2)                               *
*                   Last date of change:2 Feb 1996                   *
**********************************************************************
*                 Minami*Tateya Collaboration,  KEK, JAPAN           *
*                   E*mail:grc4f@minami.kek.jp                       *
**********************************************************************
*          Copyright  Minami*Tateya Collaboration                    *
**********************************************************************
*   J.Fujimoto, et.al. LEP-II Physics, WW-Generator, CERN 1996.      *
**********************************************************************
*   Process      : e+e- --> (3)electron (4)nu-e-bar (5)u (6)d-bar     *
*                                                                    *
*   Canonical CUT:       YES                                         *
*   Mass (Width)                                                     *
*         W-boson:  80.230(  2.034)  Z-boson:  91.189(  2.497)       *
*         u-quark:    .005           d-quark:   .010                 *
*         c-quark:   1.300           s-quark:   .200                 *
*         t-quark: 170.000           b-quark:  4.300                 *
*                                                                    *
*         alpha  :  1/128.070                                        *
*   Experimental Cuts                                                *
*        Angle Cuts                                                  *
*             Particle 3       -.985  --->      .985                *
*             Particle 4      -1.000  --->     1.000                *
*             Particle 5      -1.000  --->     1.000                *
*             Particle 6      -1.000  --->     1.000                *
*        Energy CUT                                                  *
*             Particle 3       1.000  --->   190.000                *
*             Particle 4        .000  --->   190.000                *
*             Particle 5       3.000  --->   190.000                *
*             Particle 6       3.000  --->   190.000                *
*        Invariant mass CUT                                          *
*             Inv. Mass 3-4     .001  --->   189.985                *
*             Inv. Mass 5-6    5.000  --->   189.999                *
*             Inv. Mass 3-5     .006  --->   189.990                *
*             Inv. Mass 4-6     .010  --->   189.994                *
*             Inv. Mass 3-6     .011  --->   189.995                *
*             Inv. Mass 4-5     .005  --->   189.989                *
*                                                                    *
*   OPTIONS:                                                         *
*        Calculation:         TREE                                  *
*        Anomalous Coupling:  NO                                    *
*        Coulomb Correction:  NO                                    *
*        QCD Correction:      NO                                    *
*        Gluon graph:         NO  (only for hadronic process)       *
**********************************************************************
```

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```
  ********************************************************
  *                                                      *
  *     BBBBBBB     AAAA     SSSSSS   EEEEEE   SSSSSS     *
  *     BB    BB   AA  AA   SS    SS  EE      SS    SS     *
  *     BB    BB  AA    AA  SS        EE      SS           *
  *     BBBBBBB   AAAAAAAA   SSSSSS   EEEEEE   SSSSSS     *
  *     BB    BB  AA    AA         SS  EE            SS     *
  *     BB    BB  AA    AA  SS    SS  EE      SS    SS     *
  *     BBBB BB   AA    AA   SSSSSS   EEEEEE   SSSSSS     *
  *                                                      *
  *                  BASES Version 5.1                   *
  *           coded by S.Kawabata KEK, March 1994        *
  ********************************************************
```

<< Parameters for BASES >>

(1) Dimensions of integration etc.

# of dimensions :	Ndim	=	8	(50 at max.)
# of Wilds :	Nwild	=	8	(15 at max.)
# of sample points :	Ncall	=	39366(real)	40000(given)
# of subregions :	Ng	=	48 / variable	
# of regions :	Nregion	=	3 / variable	
# of Hypercubes :	Ncube	=	6561	

(2) About the integration variables

i	XL(i)	XU(i)	IG(i)	Wild
1	.000000E+00	1.000000E+00	1	yes
2	.000000E+00	1.000000E+00	1	yes
3	.000000E+00	1.000000E+00	1	yes
4	.000000E+00	1.000000E+00	1	yes
5	.000000E+00	1.000000E+00	1	yes
6	.000000E+00	1.000000E+00	1	yes
7	.000000E+00	1.000000E+00	1	yes
8	.000000E+00	1.000000E+00	1	yes

(3) Parameters for the grid optimization step
Max.# of iterations: ITMX1 = 7
Expected accuracy : Acc1 = .1000 %

(4) Parameters for the integration step
Max.# of iterations: ITMX2 = 15
Expected accuracy : Acc2 = .0500 %

<< Computing Time Information >>

(1) For BASES H: M: Sec
Overhead : 0: 0: 0.04
Grid Optim. Step : 0:54: 0.53
Integration Step : 2: 6:30.43
Go time for all : 3: 0:31.00

(2) Expected event generation time
Expected time for 1000 events : 18.36 Sec

Date: 96/ 2/ 5 17:27

Convergency Behavior for the Grid Optimization Step

<- Result of IT	Eff	R_Neg	each iteration -> Estimate	Acc %	<- Cumulative Result Estimate(+- Error)order	-> Acc %	< CPU time > (H: M: Sec)
1	18	.00	6.777E-01	2.071	6.777356(+- .140389)E-01	2.071	0: 1:52.38
2	84	.00	6.928E-01	.648	6.913652(+- .042747)E-01	.618	0: 9:52.98
3	86	.00	6.947E-01	.533	6.932765(+- .027989)E-01	.404	0:18: 4.99
4	92	.00	6.901E-01	.444	6.918370(+- .020668)E-01	.299	0:26:55.71
5	94	.00	6.896E-01	.413	6.910548(+- .016720)E-01	.242	0:35:54.74
6	95	.00	6.860E-01	.513	6.901197(+- .015105)E-01	.219	0:44:59.96
7	94	.00	6.981E-01	.783	6.906845(+- .014559)E-01	.211	0:54: 0.53

Date: 96/ 2/ 5 17:27

Convergency Behavior for the Integration Step

<- Result of IT	Eff	R_Neg	each iteration -> Estimate	Acc %	<- Cumulative Result Estimate(+- Error)order	-> Acc %	< CPU time > (H: M: Sec)
1	88	.00	6.870E-01	.723	6.870441(+- .049666)E-01	.723	1: 2:24.93
2	88	.00	6.918E-01	.723	6.894173(+- .035247)E-01	.511	1:10:51.48
3	88	.00	6.878E-01	.710	6.888702(+- .028577)E-01	.415	1:19:17.98
4	88	.00	6.897E-01	.937	6.890082(+- .026136)E-01	.379	1:27:44.75
5	88	.00	6.868E-01	.669	6.884589(+- .022722)E-01	.330	1:36:10.48
6	88	.00	6.891E-01	.695	6.885740(+- .020527)E-01	.298	1:44:36.85
7	88	.00	6.902E-01	.699	6.888267(+- .018890)E-01	.274	1:53: 2.07
8	88	.00	6.919E-01	.708	6.892296(+- .017625)E-01	.256	2: 1:28.62
9	88	.00	6.900E-01	.709	6.893157(+- .016582)E-01	.241	2: 9:54.80
10	88	.00	6.821E-01	.667	6.884725(+- .015581)E-01	.226	2:18:19.24
11	88	.00	6.898E-01	.657	6.886173(+- .014734)E-01	.214	2:26:45.13
12	88	.00	7.002E-01	.759	6.894471(+- .014198)E-01	.206	2:35:11.51
13	88	.00	7.016E-01	.698	6.903859(+- .013637)E-01	.198	2:43:38.96
14	88	.00	6.883E-01	.672	6.902177(+- .013080)E-01	.190	2:52: 4.76
15	88	.00	6.851E-01	.694	6.898595(+- .012611)E-01	.183	3: 0:30.96

******** Contents of the histogram Header *********

(1) Actual Buffer size   =   9269 Words
(2) Contents of Histograms
    Max. No. of Histograms =   50
    Number   of Histograms =   12

ID	X_min	X_max	X_bin	Hash	Hst#
1	.0000E+00	1.9000E+02	50	2 2	1
14	.0000E+00	1.9000E+02	50	2 2	11
2	.0000E+00	1.9000E+02	50	3 2	2
15	.0000E+00	1.9000E+02	50	3 2	12
3	.0000E+00	1.9000E+02	50	4 1	3
4	.0000E+00	1.9000E+02	50	5 1	4
5	-1.0000E+00	1.0000E+00	50	6 1	5
6	-1.0000E+00	1.0000E+00	50	7 1	6
7	-1.0000E+00	1.0000E+00	50	8 1	7
8	-1.0000E+00	1.0000E+00	50	9 1	8
9	.0000E+00	1.9000E+02	50	10 1	9
10	.0000E+00	1.9000E+02	50	11 1	10

(3) Contents of Scatter Plots
    Max. No. of Scat_Plots =   50
    Number   of Scat_Plots =   0

Histogram (ID = 1) for Energy of Particle 3

Linear Scale indicated by "*"

```
    x      d(Sigma)/dx      .0E+00      6.2E-03     1.2E-02      1.9E-02
+-------+-----------------+-----------+-----------+-----------+-----------+
I  E  2 I  .000        E  0I                                               I
I  .000 I 2.863+- .960 E -4I*OOOOOOOOOOOOOOOOOOOOOOOOOO                    I
I  .038 I 3.338+- .512 E -4I*OOOOOOOOOOOOOOOOOOOOOOOOOO                    I
I  .076 I 3.740+- .532 E -4I*OOOOOOOOOOOOOOOOOOOOOOOOOO                    I
I  .114 I 3.071+- .225 E -4I*OOOOOOOOOOOOOOOOOOOOOOOOOO                    I
I  .152 I 3.381+- .147 E -4I*OOOOOOOOOOOOOOOOOOOOOOOOOO                    I
I  .190 I 1.644+- .031 E -3I****OOOOOOOOOOOOOOOOOOOOOOOOOOOOOOOO          I
I  .228 I 6.506+- .061 E -3I**************OOOOOOOOOOOOOOOOOOOOOOOOOOOO     I
I  .266 I 7.778+- .066 E -3I****************OOOOOOOOOOOOOOOOOOOOOOOOOOOO    I
I  .304 I 8.745+- .069 E -3I******************OOOOOOOOOOOOOOOOOOOOOOOO     I
I  .342 I 9.791+- .075 E -3I********************OOOOOOOOOOOOOOOOOOOOOOO    I
I  .380 I 1.075+- .008 E -2I**********************OOOOOOOOOOOOOOOOOOOOO    I
I  .418 I 1.194+- .008 E -2I************************OOOOOOOOOOOOOOOOOOO    I
I  .456 I 1.300+- .009 E -2I**************************OOOOOOOOOOOOOOOOO    I
I  .494 I 1.441+- .009 E -2I****************************OOOOOOOOOOOOOOO   I
I  .532 I 1.556+- .009 E -2I******************************OOOOOOOOOOOOO   I
I  .570 I 1.707+- .010 E -2I********************************OOOOOOOOOOO  I
I  .608 I 1.850+- .011 E -2I**********************************OOOOOOOOO  I
I  .646 I 1.931+- .011 E -2I************************************OOOOOOOO  I
I  .684 I 1.884+- .011 E -2I************************************OOOOOOOO  I
I  .722 I 5.370+- .068 E -3I***********OOOOOOOOOOOOOOOOOOOOOOOOOOOOO      I
I  .760 I 4.849+- .223 E -4I*OOOOOOOOOOOOOOOOOOOOOOOOOOOOOOOO             I
I  .798 I 1.614+- .114 E -4I*OOOOOOOOOOOOOOOOOOOOOOO                      I
I  .836 I 6.826+- .689 E -5I*OOOOOOOOOOOOOOOOOO                           I
I  .874 I 2.196+- .297 E -5I*OOOOOOOOOOOOO                                I
I  .912 I 6.076+-2.383 E -6I*OOOOOOOO                                     I
I  .950 I  .000+- .000 E  0I                                              I
I  .988 I  .000+- .000 E  0I                                              I
I 1.026 I  .000+- .000 E  0I                                              I
I 1.064 I  .000+- .000 E  0I                                              I
I 1.102 I  .000+- .000 E  0I                                              I
I 1.140 I  .000+- .000 E  0I                                              I
I 1.178 I  .000+- .000 E  0I                                              I
I 1.216 I  .000+- .000 E  0I                                              I
I 1.254 I  .000+- .000 E  0I                                              I
I 1.292 I  .000+- .000 E  0I                                              I
I 1.330 I  .000+- .000 E  0I                                              I
I 1.368 I  .000+- .000 E  0I                                              I
I 1.406 I  .000+- .000 E  0I                                              I
I 1.444 I  .000+- .000 E  0I                                              I
I 1.482 I  .000+- .000 E  0I                                              I
I 1.520 I  .000+- .000 E  0I                                              I
I 1.558 I  .000+- .000 E  0I                                              I
I 1.596 I  .000+- .000 E  0I                                              I
I 1.634 I  .000+- .000 E  0I                                              I
I 1.672 I  .000+- .000 E  0I                                              I
I 1.710 I  .000+- .000 E  0I                                              I
I 1.748 I  .000+- .000 E  0I                                              I
I 1.786 I  .000+- .000 E  0I                                              I
I 1.824 I  .000+- .000 E  0I                                              I
I 1.862 I  .000+- .000 E  0I                                              I
I  E  2 I  .000        E  0I                                              I
+-------+-----------------+-----------+-----------+-----------+-----------+----+
    x      d(Sigma)/dx     1.0E-06     1.0E-05    1.0E-04    1.0E-03
                             Logarithmic Scale indicated by "O"
```

```
**********************************************************************
*-------------------------------------------------444--------########-*
*-----------------------------------------------44444-------###----##-*
*---######---------##--##------#####----------444--44----##########---*
*-####---#######--##########--####---###------444----44-------###-------*
*-###------##------###------###------##----44444444444444----###-------*
*--##########------###------###------------44444444444444----###-------*
*-####------------###------#######---###------------44-------###-------*
*-#############--#######------########--------------44----#########----*
*-##--------###-------------------------------------------------------*
*-############-------------------------------------------------------*
*---------------------------------------------- GRACE INSIDE ------*
**********************************************************************
*                      Version 1.0 (2)                               *
*                   Last date of change:2 Feb 1996                   *
**********************************************************************
*                 Minami*Tateya Collaboration,  KEK, JAPAN           *
*                   E*mail:grc4f@minami.kek.jp                       *
**********************************************************************
*          Copyright  Minami*Tateya Collaboration                    *
**********************************************************************
*   J.Fujimoto, et.al. LEP-II Physics, WW-Generator, CERN 1996.      *
**********************************************************************
*   Process      : e+e- --> (3)electron (4)nu-e-bar (5)u (6)d-bar     *
*                                                                    *
*   Canonical CUT:       YES                                         *
*   Mass (Width)                                                     *
*         W-boson:  80.230(  2.034)  Z-boson:  91.189(  2.497)       *
*         u-quark:    .005           d-quark:   .010                 *
*         c-quark:   1.300           s-quark:   .200                 *
*         t-quark: 170.000           b-quark:  4.300                 *
*                                                                    *
*         alpha  :  1/128.070                                        *
*   Experimental Cuts                                                *
*        Angle Cuts                                                  *
*             Particle 3       -.985  --->      .985                *
*             Particle 4      -1.000  --->     1.000                *
*             Particle 5      -1.000  --->     1.000                *
*             Particle 6      -1.000  --->     1.000                *
*        Energy CUT                                                  *
*             Particle 3       1.000  --->   190.000                *
*             Particle 4        .000  --->   190.000                *
*             Particle 5       3.000  --->   190.000                *
*             Particle 6       3.000  --->   190.000                *
*        Invariant mass CUT                                          *
*             Inv. Mass 3-4     .001  --->   189.985                *
*             Inv. Mass 5-6    5.000  --->   189.999                *
*             Inv. Mass 3-5     .006  --->   189.990                *
*             Inv. Mass 4-6     .010  --->   189.994                *
*             Inv. Mass 3-6     .011  --->   189.995                *
*             Inv. Mass 4-5     .005  --->   189.989                *
*                                                                    *
*   OPTIONS:                                                         *
*        Calculation:         TREE                                  *
*        Anomalous Coupling:  NO                                    *
*        Coulomb Correction:  NO                                    *
*        QCD Correction:      NO                                    *
*        Gluon graph:         NO  (only for hadronic process)       *
**********************************************************************
```

Date: 96/ 2/ 6 10:41

```
******************************************************
*                                                    *
*    SSSSS   PPPPPP   RRRRRR   IIIII  N    NN   GGGGG    *
*   SS   SS  PP   PP  RR   RR   III   NN   NN  GG   GG   *
*   SS       PP   PP  RR   RR   III   NNN  NN  GG        *
*    SSSSS   PPPPPP   RRRRR     III   NNNN NN  GG  GGGG  *
*        SS  PP       RR  RR    III   NN NNNN  GG   GG   *
*   SS   SS  PP       RR   RR   III   NN  NNN  GG   GG   *
*    SSSSS   PP       RR    RR IIIII  NN   NN   GGGGG    *
*                                                    *
*                 SPRING Version 5.1                 *
*           coded by S.Kawabata KEK, March 1994      *
******************************************************
```

```
Number of generated events    =     10000
Generation efficiency         =    16.538 Percent
Computing time for generation =   836.960 Seconds
              for Overhead    =     1.050 Seconds
              for Others      =      .420 Seconds
GO time for event generation  =   838.430 Seconds
Max. number of trials MXTRY   =        50 per event
Number of miss-generation     =        56 times
```

```
    ************* Number of trials to get an event *************
Total =     10056 events   "*" : No. of events in Linear scale.
   x      Lg(dN/dx)  dN/dx  .0E+00      6.3E+02      1.3E+03     1.9E+03
+-------+----------+-------+------------+------------+-----------+-----------+
I  .100 I 1.994E  3I   1994I************************************OOOOOOOOO
I  .200 I 1.575E  3I   1575I*******************************OOOOOOOOOOOOOOOOI
I  .300 I 1.249E  3I   1249I************************OOOOOOOOOOOOOOOOOOOO  I
I  .400 I 9.360E  2I    936I******************OOOOOOOOOOOOOOOOOOOOOOOO   I
I  .500 I 7.390E  2I    739I**************OOOOOOOOOOOOOOOOOOOOOOOO     I
I  .600 I 5.770E  2I    577I************OOOOOOOOOOOOOOOOOOOOOOOO       I
I  .700 I 4.480E  2I    448I*********OOOOOOOOOOOOOOOOOOOOOOOOOO        I
I  .800 I 4.160E  2I    416I*********OOOOOOOOOOOOOOOOOOOOOOOOO         I
I  .900 I 3.020E  2I    302I*******OOOOOOOOOOOOOOOOOOOOOOOO            I
I 1.000 I 2.650E  2I    265I******OOOOOOOOOOOOOOOOOOOOOOOO             I
I 1.100 I 2.190E  2I    219I*****OOOOOOOOOOOOOOOOOOOOOOO               I
I 1.200 I 1.910E  2I    191I****OOOOOOOOOOOOOOOOOOOOOOO                I
I 1.300 I 1.530E  2I    153I****OOOOOOOOOOOOOOOOOOOOOO                 I
I 1.400 I 1.330E  2I    133I***OOOOOOOOOOOOOOOOOOOOOO                  I
I 1.500 I 1.000E  2I    100I***OOOOOOOOOOOOOOOOOOOOO                   I
I 1.600 I 1.130E  2I    113I***OOOOOOOOOOOOOOOOOOOOOO                  I
I 1.700 I 7.800E  1I     78I**OOOOOOOOOOOOOOOOOOOOO                    I
I 1.800 I 6.200E  1I     62I**OOOOOOOOOOOOOOOOOOOO                     I
I 1.900 I 5.900E  1I     59I**OOOOOOOOOOOOOOOOOOOO                     I
I 2.000 I 4.700E  1I     47I*OOOOOOOOOOOOOOOOOOOO                      I
I 2.100 I 4.200E  1I     42I*OOOOOOOOOOOOOOOOOOOO                      I
I 2.200 I 3.300E  1I     33I*OOOOOOOOOOOOOOOOOOO                       I
I 2.300 I 2.700E  1I     27I*OOOOOOOOOOOOOOOOOO                        I
I 2.400 I 3.500E  1I     35I*OOOOOOOOOOOOOOOOOOO                       I
I 2.500 I 2.700E  1I     27I*OOOOOOOOOOOOOOOOOO                        I
I 2.600 I 2.000E  1I     20I*OOOOOOOOOOOOOOOOO                         I
I 2.700 I 2.300E  1I     23I*OOOOOOOOOOOOOOOOOO                        I
I 2.800 I 1.500E  1I     15I*OOOOOOOOOOOOOOOO                          I
I 2.900 I 9.000E  0I      9I*OOOOOOOOOOOOO                             I
I 3.000 I 2.000E  1I     20I*OOOOOOOOOOOOOOOOOO                        I
I 3.100 I 9.000E  0I      9I*OOOOOOOOOOOOO                             I
I 3.200 I 7.000E  0I      7I*OOOOOOOOOOO                               I
I 3.300 I 7.000E  0I      7I*OOOOOOOOOOO                               I
I 3.400 I 1.100E  1I     11I*OOOOOOOOOOOOOO                            I
I 3.500 I 6.000E  0I      6I*OOOOOOOOOO                                I
I 3.600 I 6.000E  0I      6I*OOOOOOOOOO                                I
I 3.700 I 5.000E  0I      5I*OOOOOOOOO                                 I
I 3.800 I 8.000E  0I      8I*OOOOOOOOOOOO                              I
I 3.900 I 4.000E  0I      4I*OOOOOOOOO                                 I
I 4.000 I 2.000E  0I      2I*OOOO                                      I
I 4.100 I 3.000E  0I      3I*OOOOOOO                                   I
I 4.200 I 4.000E  0I      4I*OOOOOOOOO                                 I
I 4.300 I 3.000E  0I      3I*OOOOOOO                                   I
I 4.400 I 1.000E  0I      1IO                                          I
I 4.500 I 3.000E  0I      3I*OOOOOOO                                   I
I 4.600 I 6.000E  0I      6I*OOOOOOOOOO                                I
I 4.700 I 4.000E  0I      4I*OOOOOOOOO                                 I
I 4.800 I 3.000E  0I      3I*OOOOOOO                                   I
I 4.900 I 1.000E  0I      1IO                                          I
I 5.000 I  .000E  0I      0I                                           I
I  E  1 I 5.600E  1I     56I**OOOOOOOOOOOOOOOOOOOOOO                   I
+-------+----------+-------+--------------+-------------+-------------+---+
   x      Lg(dN/dx)  dN/dx 1.0E+00         1.0E+01        1.0E+02
                           "O" : No. of Events in Log. scale.
```

```
    *********  Contents of the histogram Header *********

(1) Actual Buffer size     =   9269 Words
(2) Contents of Histograms
    Max. No. of Histograms =     50
    Number   of Histograms =     12
   ID     X_min        X_max    X_bin Hash Hst#
    1    .0000E+00   1.9000E+02   50  2  2    1
   14    .0000E+00   1.9000E+02   50  2  2   11
    2    .0000E+00   1.9000E+02   50  3  2    2
   15    .0000E+00   1.9000E+02   50  3  2   12
    3    .0000E+00   1.9000E+02   50  4  1    3
    4    .0000E+00   1.9000E+02   50  5  1    4
    5  -1.0000E+00   1.0000E+00   50  6  1    5
    6  -1.0000E+00   1.0000E+00   50  7  1    6
    7  -1.0000E+00   1.0000E+00   50  8  1    7
    8  -1.0000E+00   1.0000E+00   50  9  1    8
    9    .0000E+00   1.9000E+02   50 10  1    9
   10    .0000E+00   1.9000E+02   50 11  1   10
(3) Contents of Scatter Plots
    Max. No. of Scat_Plots =     50
    Number   of Scat_Plots =      0
```

Original Histogram (ID = 1) for Energy of Particle 3
Total = 10000 events "*" : Orig. Dist. in Log Scale.

```
   x      d(Sig/dx)  dN/dx 1.0E-06     1.0E-05    1.0E-04    1.0E-03
+-------+----------+-------+-----------+----------+----------+----------+----+
I  E  2 I  .000E  0I      0I                                               I
I  .000 I 2.863E -4I      4I*****************<**O*>*****                   I
I  .038 I 3.338E -4I     14I************************<O>*                    I
I  .076 I 3.740E -4I      9I*********************<*O>***                   I
I  .114 I 3.071E -4I     14I************************<O>                     I
I  .152 I 3.381E -4I     14I************************<O>*                    I
I  .190 I 1.644E -3I     84I*********************************<>            I
I  .228 I 6.506E -3I    380I*****************************************O     I
I  .266 I 7.778E -3I    380I*****************************************O*    I
I  .304 I 8.745E -3I    547I*********************************************O    I
I  .342 I 9.791E -3I    508I*****************************************<>    I
I  .380 I 1.075E -2I    606I*********************************************<>   I
I  .418 I 1.194E -2I    689I*********************************************O   I
I  .456 I 1.300E -2I    697I*********************************************O   I
I  .494 I 1.441E -2I    784I*********************************************<>  I
I  .532 I 1.556E -2I    856I*********************************************O  I
I  .570 I 1.707E -2I    964I*********************************************<> I
I  .608 I 1.850E -2I   1006I*********************************************O I
I  .646 I 1.931E -2I   1037I*********************************************O I
I  .684 I 1.884E -2I   1048I*********************************************O I
I  .722 I 5.370E -3I    306I*****************************************O      I
I  .760 I 4.849E -4I     34I****************************<>                  I
I  .798 I 1.614E -4I     13I**********************< O>                     I
I  .836 I 6.826E -5I      5I******************<**O >                       I
I  .874 I 2.196E -5I      1I************O*  >                              I
I  .912 I 6.076E -6I      0I*********                                      I
I  .950 I  .000E  0I      0I                                               I
I  .988 I  .000E  0I      0I                                               I
I 1.026 I  .000E  0I      0I                                               I
I 1.064 I  .000E  0I      0I                                               I
I 1.102 I  .000E  0I      0I                                               I
I 1.140 I  .000E  0I      0I                                               I
I 1.178 I  .000E  0I      0I                                               I
I 1.216 I  .000E  0I      0I                                               I
I 1.254 I  .000E  0I      0I                                               I
I 1.292 I  .000E  0I      0I                                               I
I 1.330 I  .000E  0I      0I                                               I
I 1.368 I  .000E  0I      0I                                               I
I 1.406 I  .000E  0I      0I                                               I
I 1.444 I  .000E  0I      0I                                               I
I 1.482 I  .000E  0I      0I                                               I
I 1.520 I  .000E  0I      0I                                               I
I 1.558 I  .000E  0I      0I                                               I
I 1.596 I  .000E  0I      0I                                               I
I 1.634 I  .000E  0I      0I                                               I
I 1.672 I  .000E  0I      0I                                               I
I 1.710 I  .000E  0I      0I                                               I
I 1.748 I  .000E  0I      0I                                               I
I 1.786 I  .000E  0I      0I                                               I
I 1.824 I  .000E  0I      0I                                               I
I 1.862 I  .000E  0I      0I                                               I
I  E  2 I  .000E  0I      0I                                               I
+-------+----------+-------+-----------+----------+----------+----------+----+
   x      d(Sig/dx)  dN/dx    "O" : Generated Events.( Arbitrary unit in Log )
```